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120 YEARS OF STRUCTURAL FIRE TESTING: MOVING AWAY FROM THE STATUS QUO

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Abstract. During the late 19th Century, stakeholders from the building construction industry were in need of rational, quantified, and repeatable assessment of building materials and structures subject to heating during fire; thus the standard fire resistance test was born within the context of the knowledge available at that time. This paper briefly illustrates the early conception and evolution of the standard fire resistance test and presents a new fire testing methodology, named the Heat-Transfer Rate Inducing System (H-TRIS), developed to address shortcomings of the 'standard' procedure using an innovative thermal loading technique in which the thermal exposure is actively controlled not using gas phase temperature, but by incident heat flux measurements at the test element's exposed surface using a high precision loop feedback system. H-TRIS is based on the use of a mobile array of propane-fired high performance radiant heating elements, along with a computer-controlled mechanical linear motion system, allowing the development of rational fire resistance studies with high repeatability, realistic boundary conditions, and good statistical confidence, all at low economical and temporal cost.

Keywords: H-TRIS, heat flux, standard fire resistance test, structural fire resistance.

1. INTRODUCTION

Towards the end of the 19th Century, a need to provide fire safety to buildings and cities had crossed the boundaries of engineering and became a social requirement in the rapidly growing building construction community [1]. As the response from the structural fire engineering community, to overcoming the numerous inherent complexities in understanding the behaviour of real buildings in real fires, the standard fire resistance test was developed and adopted, becoming globally the predominant means of characterizing the response of structural elements and materials in fires [2], [3], [4].

For more than 100 years, the standard fire resistance test has been the backbone of the design process of structures' resistance in fire. The current test methodology remains (largely) unchanged since its initial development, despite enormous advances in fire safety science, and knowledge of the thermo-mechanical response of construction materials and structural fire modelling [1]. As noted by structural fire engineering researchers in the early 1970s: *"…it always must be borne in mind that in a strict sense standard fire endurance is not a measure of the actual performance of an element in fire, and, furthermore, that it is not even a perfect measure for comparison"* [5].

This paper presents the initial efforts and subsequent investments in developing what we now recognize as the standard fire resistance test. A brief illustration of how the industry evolved around this test, carrying with it issues which are inherent to the fundamentals behind standard fire resistance testing. A novel fire testing methodology is presented, named the Heat-Transfer Rate Inducing System (H-TRIS), which was developed to address these and other issues - by fundamentally changing the method and control by which materials or assemblies are "heated" during testing.

2. HOW DID WE GET HERE

During the late 19th Century, an era of rapid innovation within the construction industry, brought on by novel lightweight structural designs with structural configurations and materials developed in efforts to save space and build higher, promoted the early developments of *"fire-resistant"* construction. So called *"fire and water"* tests became a common practice for manufacturers of these emerging fire-resisting materials and systems, attempting to advertise their products' *"fire proof"* characteristics and resorting to whatever they considered the most satisfactory means of advertisement [6]. Private testing for the purposes of advertisement soon (and predictably) became unreliable. The establishment of federal, municipal, and private experimental testing facilities, with recognised credentials and impartiality, introduced an environment in which testing facilities could systematically test materials and systems under presumed 'uniform' conditions, initially for the purposes of comparative examination only. At the time, no standard failure criteria were defined for tested elements, although techniques for the assessment of load bearing capacity, integrity, and insulation where already common practice in these testing facilities [7].

During the early 1900s, efforts were made both by American and European testing organizations, as well as by other stakeholders involved in the building construction community, to define a uniform 'standard' fire resistance test [6], [7], [8][9]. As indicated by Ira Woolson, then Chairman of the National Fire Protection Association's (NFPA) Committee on Fire-Resistive Construction, the overarching goal of these efforts was to *"unify all fire tests under one single standard and remove an immense amount of confusion within the fire testing community"* [10]. In 1903, at the International Fire Prevention Congress held in London, UK, Edwin Sachs presented a set of suggested standards for a fire resistance test which proposed the use of an essentially arbitrary *"fierce"* fire represented by a standard time-temperature curve, as well as suggesting minimum requirements for fire resistance of structural elements, for which the level of 'protection' was classified as 'temporary', 'partial' or 'full' [6]. In the US, this was gradually adopted during the second decade of the 20th Century, as seen from transcripts of the discussions which took place at several annual meetings of the National Fire Protection Association [10]. At the 1917 NFPA annual meeting, Woolson stated that; *"we want to get it as nearly right as possible before it is finally adopted, because, after it is adopted by these various associations, it will be pretty hard to change it"*.

In the US, the Committee on Fireproofing of the American Society for Testing and Materials (ASTM) agreed to adopt a single standard time-temperature curve, and stated that the gas phase temperature fixed by the curve should be controlled by the average temperature shown by at least three thermocouples situated six inches from the surface of the test specimen [10]. This committee gathered representatives from NFPA, ASTM, Underwriters' Laboratories (UL), the American Concrete Institute (ACI), and other stakeholders to agree the standard methods. With an agreed standard fire resistance test method, subsequent decades saw the fire testing community experience considerable growth and inertia in the number of costly standard fire testing facilities around the world.

In 1928, on the basis of a recognition that the standard time-temperature curve was not a 'real' fire, Simon Ingberg presented a method for gauging fires' 'severity' resulting from the burnout of all the contents of a compartment, and attempted to relate this to the severity of heating imposed during the standard fire resistance test [11]. Thus, Ingberg introduced the 'Equal Area Concept' which, in theory, allowed designers to define the required time of standard fire resistance for structural elements based on the actual fuel load within a given compartment [11]. Even though it was not obvious, Ingberg's publications on the topic fundamentally (and unfortunately) linked the concept of 'time' to the performance objectives used to define fire resistance.

For the remainder of the 20th century, various practitioners and researchers including Kunio Kawagoe, Tibor Harmathy, Philip Thomas, Margaret Law, and many others, noted and demonstrated numerous fundamental concerns with the standard fire resistance test and the design process used to define and verify structures' fire resistance [5], [12], [13], [14], [15]. This resulted in a number of research studies intended to improve and rationalise the standard fire resistance test [16]. These studies lead to significant enhancements on furnaces' thermal loading homogeneity (e.g. introduction of the plate thermometer as a measuring device and controller of the gas phase temperature inside furnaces). However, high operating costs, poor repeatability, unrealistic and/or inappropriate boundary conditions, and poor statistical confidence remain, to this day, common problematic issues regarding the use of standard fire resistance tests for design, product development, and rational, defensible scientific structural fire engineering research.

In today's modern era, the status quo of the fire safety design community is a system in which the required rating (i.e. time to *'failure'* in the standard fire resistance test) of structural elements is, in most cases, defined implicitly based on the type of occupancy, size of the compartment, geometry of the building, use of suppression systems (i.e. sprinklers), ease of fire brigade intervention, and many other factors. Some design standards even allow for trade-offs between various fire safety systems (e.g. reduce the required rating for a given structural element if a suppression system is used). The concept of the standard fire resistance test has gradually evolved during the decades since its initial development, and it is now being used well outside its original applicability or its original intent. It is thus important to revisit this test method and question more than one hundred years of the status quo, so that we, as an industry, might avoid the false presumption that a compliant building is necessarily a 'good' or 'safe' building (which it is not assuredly) and might better optimise the design and construction of buildings for improved functionality, durability, aesthetics, and sustainability.

3. H-TRIS

The new test methodology, H-TRIS, uses a mobile array of propane-fired high performance radiant heaters, along with a mechanical linear motion system (Figure 1). Thermal loading of test samples is *actively* controlled using incident heat flux (i.e. thermal energy) measurements taken from two water cooled Schmidt-Boelter heat flux sensors. These are placed at specimen's exposed surface, and using a high precision loop feedback system the linear motion system is computer-controlled in real time to adjust the heaters' location (i.e. distance from the sample) to follow any pre-defined time-heat flux relationship. H-TRIS thus allows accurate *quantification* of the thermal *energy* absorbed by a tested element with precision and repeatability; all at negligible economical and temporal costs in comparison to a standard fire resistance (i.e. furnace) test.

The most significant improvement provided by this new testing methodology is the way in which specimens are heated. In a standard fire resistance test, very powerful burners (gas or oil fuelled) are used to blow hot gases inside a prism shaped furnace. When testing walls or floors, one of the furnace's major boundaries is totally or partially replaced by the specimen being tested. The furnace itself becomes a heat transfer system, creating fundamental differences in how standard and repeatable the thermal energy being absorbed by the specimen really is. This was openly discussed during the 1970s and 1980s [16], and remains a topic of concern and debate within the fire testing community.

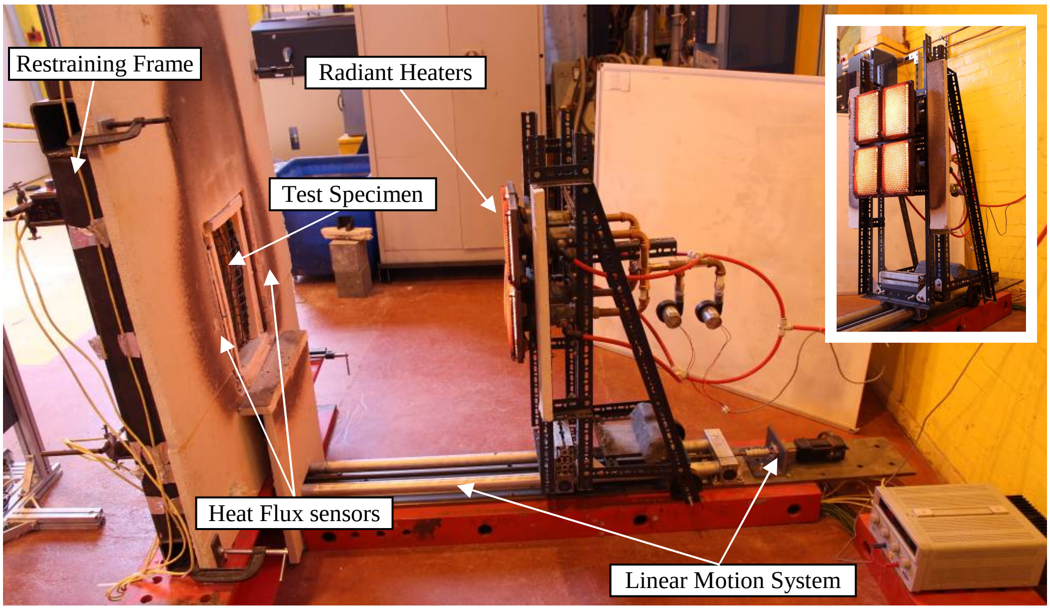

Figure 1: Heat-Transfer Rate Inducing System (H-TRIS).

At The University of Edinburgh, a research project was undertaken, meant to replicate the thermal conditions (i.e. internal thermal gradients) experienced during a standard fire resistance test in a large scale floor testing furnace [16]. The project was actually concerned with replication of furnace tests' thermal conditions for the purposes of evaluating the propensity of different concrete mixes to explosive cover spalling, however this is not critical for the purposes of the current paper. During the project, a direct comparison was made between internal temperatures (at depths of 10, 20 and 45 mm from the exposed surface) recorded inside high performance, 45 mm thick concrete panels heated from one side using H-TRIS, and those recorded during furnace tests of effectively identical concrete elements [17]. The resulting comparison is shown in Figure 2, where it is clear that H-TRIS imposes thermal gradients within the test specimens which are similar to those imposed in the furnace tests; thus partially validating the use of this technique, particularly in replicating the thermal loading imposed by any particular furnace. Furthermore, Figure 2 illustrates the high repeatability of H-TRIS tests as compared with the scatter seen in the furnace tests, for a range of measured temperatures in identical specimens. Additional validation studies have been performed or are currently underway; these will be reported elsewhere.

H-TRIS presents an opportunity for a more correct determination of materials' properties subject to severe heating and a more complete understanding of thermal phenomena that depend on the thermal loading (e.g. fire induced concrete spalling, intumescent fire protection systems' behaviour, etc). H-TRIS potentially allows researchers to tackle some of the concerns inadvertently created during the gradual evolution of the standard fire resistance test, as indicated above, basing testing on a 'real' fire's time history of heat flux, and implementing a truly repeatable methodology than can potentially achieve Ingberg's intent: to describe the performance objectives used to define fire resistance on the basis of 'burnout' (i.e. complete combustion of everything that can burn inside the compartment) in a real fire [11].

With H-TRIS, structural and non-structural materials can now be tested at negligible economical and temporal cost relative to large scale standard fire resistance testing. Thus, for the first time at this scale, the quantification of the thermal energy absorbed can be known with repeatability and confidence. Consequently, H-TRIS is generating considerable interest from varied sectors within the building construction industry.

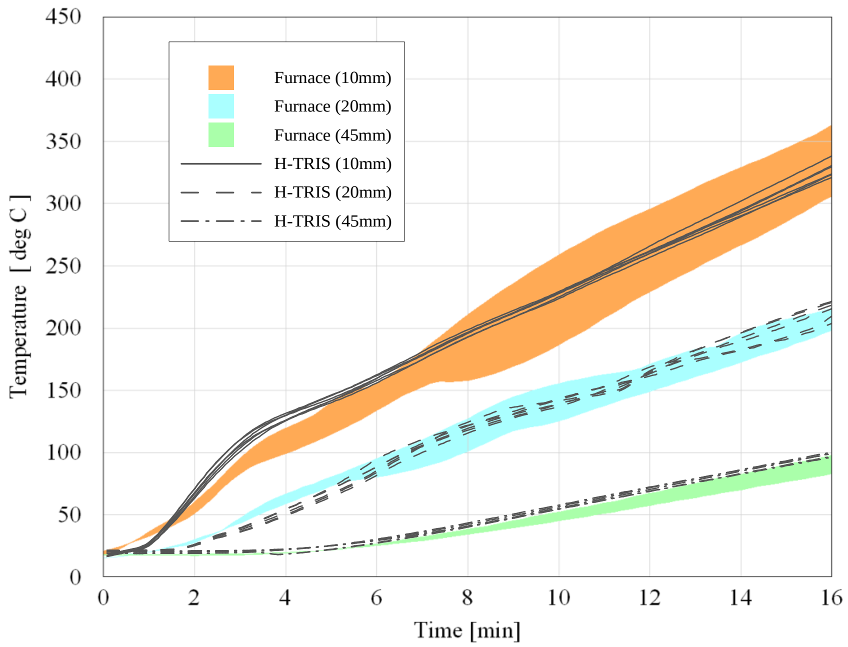

Figure 2: Comparison of concrete specimens' internal temperatures recorded in a standard fire testing furnace following the ISO 834 standard fire as compared against H-TRIS test results based on simulation of the furnace test.

4. CONCLUSIONS

This paper has briefly reviewed the historical basis and evolution of the standard fire resistance test, and outlined some of the important issues around its use and outcome (i.e. fire rating), as the root for describing the performance objectives used to define fire resistance.

Experimental tools able to conduct fire resistance studies with high repeatability, realistic boundary conditions, and high statistical confidence, all at low economical and temporal cost, will allow product manufacturers to develop products to perform in real conditions, allow designers and regulators to produce and approve systems with an understanding of the real levels of safety, and allow researchers to correctly define materials' properties and systems' behaviour in real, credible worst-case design fire conditions. H-TRIS is nothing more than a tool that attempts to fill these needs in a manner which is explicitly based on absorbed heat flux (i.e. thermal energy absorbed by materials) and which, unlike standard fire testing furnaces, treats all materials and systems equally for the same presumed fire conditions.

This paper briefly demonstrates that H-TRIS is capable of satisfactory reproducing the thermal conditions experienced within a test specimen that would be observed during a standard furnace test. Furthermore, it is able to reproduce these conditions rationally, quickly, repeatably, and at a fraction of the cost of large scale furnace testing.

5. ACKNOWLEDGMENTS

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REFERENCES

[1] Gales J., Maluk C., Bisby L.; Large-Scale Structural Fire Testing – How did we get here, where are we, and where are we going?, *Symposia on Fire Testing and Experimental Validation as part of The 15th International Conference on Experimental Mechanics (ICEM15)*, Porto, Portugal, July 22-27 2012, 22pp.

[2] Woolson I.; Dwelling Houses: A code of Suggestions for constructions and fire protection recommended by the National Board of Fire Underwriters, *American Institute of Architects*, New York, 1916, 137 pp.

[3] ISO; ISO 834-1:1999: Fire Resistance Tests - Elements of Building Construction – Part 1: General Requirements. *International Organization for Standardization*, Geneva, Switzerland, 1999, 26pp.

[4] ASTM; ASTM E119-11a: Standard methods of fire test of building construction and materials, *American Society for Testing and Materials*, West Conshohocken, PA, 2011, 34pp.

[5] Harmathy T.Z., Lie T.T.; Fire Test Standard in the Light of Fire Research, *ASTM Special Technical Publication 464*, 1970, pp. 85-97.

[6] Kendall J.; Fire Prevention and Fire Protection as Applied to Building Construction – A handbook of Theory and Practice, John Wiley & Sons, NY, 1912.

[7] Woolson I.H.; Columbia University Introduces an Educational Innovation, *New York Tribune*, September 18 1904. Available via http://chroniclingamerica.loc.gov/lccn/sn83030214/1904-09-18/ed-1/seq-30/.

[8] Sachs, E.O.; Suggested Standards of Fire Resistance, *Report on Proceedings of the International Fire Prevention Congress*, London, England, July 6-11 1903, pp. 243-248.

[9] Welch, Commandant; The Need for a Uniform Method of Testing the Fire Resistance of Building Materials, with Discussion, , *Report on Proceedings of the International Fire Prevention Congress*, London, England, July 6-11 1903, pp. 249-252.

[10] NFPA; Reports of the Committee on Fire-Resistive Construction, *Proceedings of the National Fire Protection Association Annual Meetings*, US, 1917-1930. Available via http://www.nfpa.org.

[11] Ingberg S.; Tests of the Severity of Building Fires, *NFPA Quarterly*, 22, 1928, pp. 43-61.

[12] Law M.; Designing fire safety for steel – recent work, *Proceedings of the ASCE Spring Convention, American Society of Civil Engineers*, New York, 1981, 16pp.

[13] Law M., Beever P.; Magic Numbers and Golden Rules, *Proceedings of the Fire Safety Science Fourth International Symposium*, Ottawa, Canada, 1994, pp. 79-84.

[14] Thomas P.H.; What is needed in fire science, *Proceedings of the 'New Technology to Reduce Fire Losses & Costs' Conference*, Luxembourg, 1986, pp. 1-7.

[15] Kawagoe K.; Fire Behaviour in Rooms, *Report of the Building Research Institute No 27*, Japan, September 1958, 73pp.

[16] Maluk C., Bisby L., Terrasi G., Krajcovic M., Torero J.L.; Novel Fire Testing Methodology: Why, How and What Now?, *Mini-symposium on Performance-based Fire Safety Engineering of Structures as part of The 1st International Conference on Performance Based and Life Cycle Structural Engineering (PLSE)*, Hong Kong, December 5-7 2012, 11pp.

[17] Terrasi G.P., Bisby L., Barbezat M., Affolter C. and Hugi E.; Fire Behavior of Thin CFRP Pretensioned High Strength Concrete Slabs, *Journal of Composites for Construction*, 16 (4), 2012, pp. 381–394.